

REMOTE SENSING AT THE UNIVERSITY OF KANSAS IN RADAR SYSTEMS

by

Richard K. Moore
Center for Research, Inc.
University of Kansas
Lawrence, Kansas

INTRODUCTION

Remote sensing research at The University of Kansas is a multidisciplinary effort involving the interaction of radar engineers, data processing engineers, and geoscientists who approach remote sensing as a systems problem. We believe that the interfaces between target-sensor interaction, sensor research, data processing, and geoscience user interpretation can best be solved by such a team effort. Figure 1 illustrates the remote sensing system as we view it.

Objects to be viewed are selected by the interpreters. The subject of target-sensor interaction is a most important one. This interaction determines the way in which the sensor views the object and consequently the way in which the interpreter can use the sensor for studying the object. Sensor development is another activity in the system. When the sensor produces images in multiple wavelengths or polarizations, or even at a single wavelength and polarization at multiple times, the images must be brought to congruence before they can be automatically processed with pattern recognition techniques. Multiple images almost demand automatic processing because of the difficulty for the human interpreter to relate one image to the other. Analog processing can be in almost real time, but digital processing permits great flexibility. We believe the digital techniques should be used to establish appropriate algorithms for particular data sets but that analog techniques should be then applied to processing the large mass of data. The data are useless to the interpreter unless displayed in an easily understood fashion; thus displays are an important part of the remote sensing system. Interpretation at any time after generation of the display requires the use of recorders, varying from a simple camera to an elaborate magnetic recording system. Automatic processing of data requires calibration throughout the system — unfortunately, this has not been widely used in remote sensing in the past. Interpreters should contribute significantly to the development and adjustment of the sensors, congruencers, processors, and displays since they are the ultimate users.

At The University of Kansas we engage in object-sensor interaction studies, in sensor development, and in image processing using both digital and analog pattern recognition techniques with displays ranging from computer printouts to color television screens. We have studied the congruencing problem but are not working on it. Our interpreters (geologists and geographers) interact closely with the engineers engaged both in the sensor development and the data processing equipment and technique development.

This paper confines itself to a discussion of our radar system research, including object-sensor interaction and sensor development. The papers by Kelly and Morain describe other aspects of our research.

OBJECT-SENSOR INTERACTION

Table I summarizes the FY70 research at the University of Kansas in object-sensor interaction. Much of the theoretical work has been supported by the National Science Foundation and by the U. S. Army. Most of the experimental work reported here has been supported by NASA, but development of the radar spectrometer received both Army and NASA support.

Because of the limited time available, only the octave bandwidth spectral response experiment is reported here. Other activities listed have been or will be reported in technical reports, papers, and technical memoranda.

Spectral responses have been reported for decades over continuous bands in the visible and infrared regions. Microwave spectral response measurement however has consisted of separate widely spaced isolated wavelengths with each observation produced by a different radar or radiometer. Thus, assessment of the potential value of multi-wavelength or continuous-coverage microwave sensors has been seriously hampered because no data were available to illustrate the comparison between responses across continuous bands.

Spectral responses of remote sensing targets have been obtained over an octave bandwidth in the microwave region at The University of Kansas during the past year.¹ Figure 2 illustrates a normalized comparison of spectral responses in the optical-IR region with a comparable wavelength spread in the microwave region. The responses in the optical region govern the color; three typical ones are shown on the figure. The responses on the microwave region, therefore, determine a "microwave color" and three typical examples of these are shown in the figure. Clearly the variability in the microwave region is comparable with that

in the optical-IR region and "color" appears to be as valid a concept for microwaves as for the shorter wavelengths.

The absolute level of the microwave response varies from one object to another more than does the absolute level in the optical-IR region for typical illuminating angles. Thus, to show similarity, the curves presented had to be normalized by taking the mean response across the band as unity. The "error bars" shown on the microwave response are not caused by experimental error but rather are due to the inability to obtain sufficient bandwidth averaging. This subject is discussed later in connection with development of polypanchromatic radars.

The microwave region from 3.75 to 7.5 cm wavelength was chosen for the initial experiments because octave-bandwidth components are less readily available at shorter wavelengths. Extension of these responses to both shorter and longer wavelengths is contemplated, but shorter-wavelength equipment will work over smaller fractional bandwidths. The results will be particularly interesting, since most imaging radars used for remote sensing have operated at wavelengths of 3 cm or shorter.

RADAR SYSTEMS RESEARCH

In addition to the object-sensor interaction studies, radar systems research has been conducted at The University of Kansas over the past year, and in fact since the conception of the NASA remote sensing program in 1964. Table II summarizes the activity in radar systems during the past year. Here we discuss primarily polypanchromatic radar development and the spacecraft imaging radar studies. Brief mention is made of the comparison between real and synthetic aperture operation of the DPD-2. Our extensive work in scatterometer systems analysis is not reported here although it has been documented. The paper by Dr. Krishen in this meeting describes some similar activities at MSC. Close liaison has been maintained between the work at Kansas and that at MSC on the scatterometer system.

POLYPANCHROMATIC RADAR SYSTEM DEVELOPMENT

The potential of "radar color" has been demonstrated by the spectral response curves. To use this potential properly, however, requires adequate averaging of the radar return. Without such averaging each point in the return has an amplitude determined by one sample from a Rayleigh distribution and the result is a very speckled image.

The speckling comes about because of the use of coherent single frequency radiation.

The same sort of thing would happen if laser illumination were to be used in a still room for making photographs. Figure 3 illustrates this point. Three images are shown, one an air photo printed with white light, one an air photo printed from the same negative but with laser (monochromatic) light and one a radar like-polarized image of the same Imperial Valley area made with a typical monochromatic system. Note the speckled nature of the monochromatically printed air photo. This is due to phase interference caused by small irregularities within the negative. The comparable phase interference phenomenon occurs with radar. It too has a speckled image. Note that the radar does, however, show some features barely visible in the panchromatic photograph and invisible in the monochromatic photography. Presumably, if we were to make a panchromatic radar image of this area, speckle would disappear and the image would appear more like the panchromatic photography — within the limits imposed by the resolution of the radar.

The averaging that takes place and permits the panchromatic image to have smoother grey tones is because a broad band of frequencies is used and phase interference effects are removed by averaging on film of the responses at the different individual frequencies. With the radar one can hope to achieve this averaging either with a broad band or by other techniques. For instance, the azimuth resolution might be made better than needed and the degraded image would permit averaging together several cells of the fine-azimuth-resolution image. For a radar, averaging in frequency is equivalent to obtaining a finer range resolution than needed, with subsequent averaging together of the fine-range-resolution cells to obtain a poorer resolution with better grey scale rendition.

The effects of both frequency averaging and finer range resolution is demonstrated with Figure 4, using ultrasonic simulation.² The images shown were produced with ultrasonic waves in water at frequencies indicated. The wavelength for 1500 kHz ultrasonic waves in water is 1 mm. The top images were made with a pulse duration of 20 μ s at an angle of incidence of 30°; this gives a range resolution of 30 mm.

The target was made up to simulate a pattern of fields. Note that the small field projecting to the bottom is almost invisible in the monochromatic image and the large field projecting toward the bottom is invisible. In the panchromatic image, however, these fields show clearly and the grey scale in the larger fields is more uniform. For this image 16 independent samples are averaged per resolution element. The bottom pictures were made with a shorter pulse corresponding to a range resolution of 13.5 mm. With this finer resolution the eye is

able to distinguish the different characteristics of the small field projecting down, although it shows up better on the panchromatic image. The panchromatic image in this case is not improved as much relative to the monochromatic image because only about seven samples have been averaged for each point.

The frequency range occupied by a panchromatic image in Figure 4 has been divided into three parts to produce a color or "polypanchromatic" image. The image from each part of the spectrum was assigned a different primary color and the results were combined on the TV screen. Figure 5 shows this polypanchromatic image. The concept of radar color is shown by this picture, but the quality of the picture is lower than that of the panchromatic image from which it was derived because the amount of averaging for each cell was reduced by admitting only one-third the frequency sweep for a given component (single color) image. Thus the degree of speckle in each is mid-way between that of the monochromatic and panchromatic images of Figure 4.

The effect of using single frequencies without averaging is illustrated in Figure 6. These pictures were taken with the radar system used for determining the spectral response in Figure 2. The system was operated as a "B-scan radar" from a position atop a ten-story dormitory. In this format the vertical direction of the image is slant range and the horizontal direction is azimuth angle; consequently, close objects are spread across the image more than equal-width for objects that subtend a smaller angle.

Figure 6 shows three images made at single carrier frequencies less than 1 per cent separated. Careful examination of the images shows many differences and most of these differences are due to the phase interference phenomenon that causes speckle in monochromatic radar images. Figure 7 shows the same scene with a monochromatic and two panchromatic images. Especially striking is the filling in of the lines in the right hand part of the image on the panchromatic pictures. These lines are barriers in a parking lot and should be essentially continuous. Also notable is the shape of the structures in the center of the image. Some of them appear to have little shape in the monochromatic image but take on a clear shape in the panchromatic images.

Figure 8 shows the same thing at a higher frequency. Here the azimuth resolution is better because the same antenna was used as at 6.00 GHz. The difference in the parking lot is even more striking than before particularly for the wider bandwidth.

These illustrations clearly indicate the advantage of some sort of averaging and the fact that averaging in frequency can provide the desirable characteristic. With a real-aperture SLAR some azimuth averaging takes place automatically, but for a fine-resolution system

additional range averaging is needed to reduce speckle. With a synthetic aperture radar on the other hand, better azimuth averaging may well be possible. If so, it can be achieved without the additional power that may be required to obtain averaging in frequency.

The effect of averaging in frequency has been determined theoretically, and Figure 9 shows an example calculated from this theory. The ordinate is the variance of the received power, normalized to the square of the mean. Thus, at minimum bandwidth the variance is equal to the square of the mean. Examples are shown for range resolutions of 50 feet and 10 feet. To reduce the variance to 1 per cent (standard deviation to 10 per cent of the mean) bandwidth well in excess of 500 MHz is required for 50 foot resolution and 5 times as much bandwidth for 10 foot resolution.

The radar spectrometer was used to show this effect with returns from a grassy area as illustrated in Figure 10. The rapid fluctuations with frequency appearing in the 100 MHz curve are due to the phase interference phenomenon. Averaging with a bandwidth of 500 MHz removes most of these small-period fluctuations; presumably the remaining curve is reasonably representative of the actual mean scattering coefficient variation across the band. Note that even the 100 MHz curve represents averaging from about 2.5 independent samples and the fluctuation with this much averaging is significantly less than if the 40 MHz curve had been plotted!

Since the amount of bandwidth is limited in practical systems, and the fineness of azimuth resolution is also limited, some sort of trade-off may be necessary with radar systems for resource studies. The trade-off is between uniformity of grey tone for large homogeneous areas (and accuracy of grey tone for small objects) and resolution. Grey scale cannot be properly reproduced at the finest resolution, but degrading the resolution too far may be disastrous because boundaries or whole objects may be missed. This subject is receiving further study at The University of Kansas.

SPACECRAFT IMAGING RADAR STUDY

Digital synthetic aperture processing on board a spacecraft has been considered in a preliminary study recently completed.³ With present state of the art a digital processor for a spacecraft synthetic aperture radar appears prohibitively large both in space and in power. An adequate on-board processor may be possible by 1975, however, if the projections of this study are borne out.

A flexible computer program for simulating performance of real-aperture and synthetic-aperture radar systems was developed as part of this study. Results presented here are images printed out from this program. Application of the program to real images is prohibitively expensive; consequently, relatively simple contrived images are used in the example. Figure 11 shows three printouts from the program for a target consisting of two uniform elements with a boundary diagonally across the image. (1) is the "true image" whereas (2) and (3) show different contrasts in the output after synthetic aperture processing. The difference in appearance due to dynamic range of the output is an indication of the kind of problem that also exists with real radar images.

The simulated digital processor for spacecraft radar uses subaperture averaging to permit improved grey scale with reasonable resolutions for earth resource applications; it also reduces the amount of equipment and power required by the processor. Figure 12 illustrates the concept of subaperture processing. The largest possible synthetic aperture is the distance along the flight track during which the beam of the real antenna illuminates the desired ground object. If the synthetic aperture is "built" this long the resulting resolution, in theory, is half the length of the real antenna and the synthetic aperture radar is said to be "fully focussed." For a real antenna 4 meters long this would give an azimuth resolution of 2 meters, which would almost certainly be finer than desirable for a spacecraft system because of the vast quantity of data produced by such a fine resolution system. Thus it should be possible to average together some sizable number of the cells produced by the fully focussed processor. For the examples cited, 10 cells could be averaged together and give a 20 meter azimuth resolution.

Another way to achieve the same result involves a simpler digital processor. Portions of the available synthetic aperture are processed separately, the results stored until all processing is done, and then combined. Each subaperture has a length appropriate to the desired resolution. Thus, for the example cited 10 such subapertures would be possible. Figure 12 illustrates a system with 5 subapertures. The synthetic beam is squinted ahead for subapertures 1 and 2 and behind for subapertures 4 and 5. It is directly to the side only for subaperture 3. If only one subaperture were processed, the desired resolution (20 m for the example) would be obtained but the image would be highly speckled. The mean-to-standard deviation ratio for the image is improved by the square root of the number of independent samples averaged. Thus for the example in Figure 12, it is improved by the $\sqrt{5}$ and for the example cited above with 10 subapertures the "speckle factor" (mean-to-standard deviation ratio) is improved by $\sqrt{10}$.

Figure 13 illustrates the effect of Rayleigh-distributed scattering for a monochromatic radar with subaperture processing and shows improvements due to averaging. Although the mean scattering cross section of the image shown as (1) in the figure is a constant on each side of the boundary the speckle is severe. (2) shows results for a processing technique giving an improvement of the $\sqrt{5}$. By using two separate channels with quadrature returns for each subaperture, the improvement in speckle is increased by $\sqrt{2}$ and the result is shown in (3) in the figure. Clearly more averaging is needed to measure the mean value accurately, but the speckle has been greatly reduced by averaging.

As discussed earlier, the spacecraft radar system design involves a resolution-grey scale trade-off. To achieve better grey scale uniformity than that illustrated in the figure, resolution must be poorer (more subapertures must be used). If resolution is the important factor (as it may be for some types of problems), grey scale uniformity must suffer.

A projection was made for an electronic digital processor for spacecraft radar using assumptions about the possible electronic components available in 1975. Complementary-MOS devices are now becoming available, and it was assumed that availability of these devices would permit a storage unit with 10 μ W a bit. Subject to this assumption, the postulated radar is shown in Table III. Such a system is essentially that described in the example in the preceding paragraphs; it uses 10 subapertures rather than the 5 shown in Figure 12 and 13.

The average transmitter output power is 60 watts. The assumed transmitter draws a good deal more power from the spacecraft than 60 watts, however, and it transmits a high peak power probably in the 100's of kilowatts. The total drain for such a system, exclusive of the processor, may well exceed 300 watts. Nevertheless the total power consumption of processor and radar system would be well under 1 kW.

Such a system does not use panchromatic averaging. Panchromaticity would increase the power requirement significantly. Added center frequencies would also increase the power requirement but frequencies below 10 GHz could be added with less of a penalty than higher frequencies.

OPTIMUM DEPRESSION ANGLES FOR RADAR GEOLOGY⁴

The proper depression angle for a radar system depends upon the geometry of the terrain being imaged. In high mountains the phenomena of radar layover and shadowing make certain angles far more desirable than others. In flat country geologists would like to emphasize small

topographic differences and relatively small depression angles are called for. Application to agriculture, on the other hand, may call for larger depression angles.

Figure 14 shows the effect of different viewing angles across the swath of an imaging radar when a triangular mountain is to be imaged. At points 1 and 2 some layover exists; that is, the top of the mountain appears to be closer to the radar than the bottom, which in fact it is; but its ground distance is further than that to the bottom of the mountain. Thus, thought of in terms of a map, a radar picture is in error at these points because the top of the mountain appears in the wrong place. At angle 3 on the figure some shadow exists, and the front face of the mountain all appears at the same range even though it occupies different positions on the underlying plane. In 4 the shadow has been increased but the top and bottom of the mountains appear on the image in their correct ground-plane order, although with incorrect spacing. We are indeed fortunate that most mountains do not look like this one!

Figures 15 and 16 illustrate a map and a radar image of the same area in Alaska. This is a quite mountainous region and the result is considerable distortion at the inner edge of the image and considerable shadowing at the outer edge. Close examination of the image and the map illustrates the point.

Figure 16 was made with a "true ground range" presentation on the radar. With this type of presentation, the slant range measured by the radar is transformed prior to recording with a factor that would remove the distortion in a slant range presentation if the ground were flat. When the ground is mountainous, the net effect of the "true-ground-range" presentation is to make the image appear even more distorted than the slant-range image. The mountain peaks at the inner edge of Figure 16 show this point. In the "true-ground-range" presentation differences in slant range at the inner edge of the image are accentuated. When these are due to differences in height rather than to differences in distance along the ground this accentuates the height distortion as shown. Thus the use of "true-ground-range" presentation, while very helpful in flat terrain, may in fact be disadvantageous in mountains.

Some of these effects can also be seen in Figure 17 where two look angles about 45° apart were used to image the same area. In this case the slant-range presentation is used and the mountains in the near range do not appear as distorted as in Figure 16. Nevertheless they really are distorted and the differences are quite apparent by close examination of the two images. Furthermore, the effect of shadowing in the far range is severe. Some of the regions for which image A provides information are shadowed in B and conversely.

The study investigated the optimum radar depression angle for areas with different amounts of topographic expression. These results were compared with maps describing the relief in different parts of the world and optimum radar depression angle maps were prepared for the world as illustrated in Figures 18 and 19.

A relatively narrow range of depression angles is appropriate for some types of terrain. A radar system carried in an aircraft at moderate altitudes produces an image with a wide range of depression angles (typically from 10° or less to 65°). A comparable radar carried at higher altitude, either in a very high altitude aircraft or preferably in a spacecraft, can achieve the same swath width but have a much narrower range of depression angles. Thus, the effects of layover and shadow from one side of the image to the other should be about the same, and the appropriate depression angle can be selected for the particular terrain being imaged. Consequently, it appears that radar should be used in spacecraft because this proper choice of the depression angle is permitted for the particular problem being studied; whereas such a choice is possible for an aircraft only over a very narrow swath.

MODIFICATION OF THE DPD-2 IMAGING RADAR

The modified DPD-2 imaging radar carried on the NASA/MSC aircraft was further modified at our request during the year to permit use of both real-aperture and synthetic-aperture imaging. Previous to this modification it had only had unfocussed synthetic-aperture capability. Little or no averaging is possible even though the resolution is relatively poor, as the unfocussed technique does not take full advantage of the available time that the target is illuminated by the real aperture of the antenna. It amounts to performing an aperture synthesis over one of the subapertures shown in Figure 12, and a relatively short one at that.

The DPD-2 has been flown in the Arctic within the past year by the U. S. Coast Guard; the version used for that purpose was a real aperture system. A logarithmic IF amplifier desirable for a real-aperture system had been removed from the military version when the system was converted for use by MSC. Although the military system used this amplifier for a different purpose, it was easy to replace the amplifier in the system and provide the capability of producing both real-aperture and synthetic-aperture images with the system at MSC. The results with the real aperture system are encouraging as indicated in the subsequent paper by Dr. Morain, although some problems still remain to be worked out for the particular unit at MSC.

A flight made during the year over the Garden City, Kansas, agricultural test site permitted comparison of the images with the real-

and synthetic-aperture systems on the MSC aircraft.⁵ Figure 20 shows sample images from the two systems for the same terrain. Resolution on the synthetic-aperture system is considerably better than that for the real aperture, but the quality of the image is not as good because of the speckle in the grey scale due to insufficient averaging. The real-aperture system averages enough independent samples to produce a much better grey scale and consequently to permit better agricultural analysis.

For areas with smaller target units the synthetic-aperture system may be needed because of its finer resolution; however, for areas like that at Garden City, the real aperture system appears to give a better result because of improved averaging.

Other items in Table II will not be discussed at this time but reports are available.

CONCLUSION

Demonstration that a spectral response across an octave bandwidth in the microwave region is as variable as the comparable response in the visible and infrared region is a major mile-stone and indicates the potential of polypanchromatic radar systems is analogous with that of color photography.

Averaging of the returns from a target element appears necessary to obtain a grey scale adequate for many earth-science applications of radar systems. This result can be obtained either by azimuth averaging or by the use of panchromatic techniques (range averaging). Improvement with panchromatic techniques has been demonstrated both with a land-based electromagnetic system and with an ultrasonic simulator. The advantage of the averaging achieved in azimuth with the real-aperture version of the DPD-2 when compared with the synthetic aperture version confirms the concept.

The study of optimum radar depression angles for geologic analysis leads to the conclusion that radars for geologic analysis should be carried in space or in very high altitude aircraft so that restricted ranges of depression angles can be used over relatively wide swaths. This is important because previous discussions have indicated that a radar could just as easily be carried in a moderate-altitude aircraft. This is certainly true for some applications but it appears not to be true for geologic analysis and other earth observation type analyses that must be conducted in hilly and mountainous terrain.

Other work at The University of Kansas is reported here by Kelly and by Morain. The interaction between the radar engineers, data processing engineers, and earth scientists at The University of Kansas is, we believe, most important. Each group benefits from the others comments, and the resulting combination is stronger than its individual components.

REFERENCES

1. Waite, W. P., "Broad-Spectrum Electromagnetic Backscatter," Ph. D. Thesis, University of Kansas, 1970, Also published as CRES Technical Report 133-17, August, 1970.
2. Thomann, G. C., "Panchromatic Illumination for Radar; Acoustic Simulation of Panchromatic Radar," Ph. D. Thesis, University of Kansas, 1970, Also published by NASA/MSC as CRES Technical Report 177-11, August, 1970.
3. Gerchberg, R. W., "Synthetic Aperture Radar and Digital Processing," Ph. D. Thesis, University of Kansas, 1970, Also published by NASA/MSC as CRES Technical Report 177-10, September, 1970.
4. MacDonald, H. C. and W. P. Waite, "Optimum Radar Depression Angles for Geological Analysis," published by NASA/MSC as CRES Technical Report 177-9, August, 1970.
5. Thomann, G. C. and T. James, "Real-Aperture/Synthetic-Aperture Image Comparison," to be submitted to IEEE Letter, Trans. on Aerospace and Electronics, University of Kansas, 1971.

TABLE I

RADAR SYSTEM RESEARCH
 FY70
 UNIVERSITY OF KANSAS
 OBJECT-SENSOR INTERACTION
 THEORY
 ROUGH-SURFACE COMBINED PHYSICAL OPTICS-PERTURBATION MODEL
 VOLUME-SCATTER AND 2-ROUGH SURFACE THEORY
 APPLICATION OF VOLUME SCATTER TO ICE AND SNOW
 PHYSICAL OPTICS MODEL APPLIED TO OCEAN RADIOMETRY
 EXPERIMENT
 OCTAVE-BANDWIDTH SPECTRAL RESPONSE
 ULTRASONIC SIMULATION
 SOIL-MOISTURE DIFFERENCE INDICATIONS ON SLAR IMAGES-NEAR RANGE
 OLD SNOW DISTINGUISHED FROM NEW
 RESTUDY AND SUMMARIZE OCEAN SCATTEROMETER DATA
 APPLY PATTERN RECOGNITION TO 1967 ICE SCATTEROMETER DATA
 MISSION SUPPORT - 119(OCEAN), 126(ICE), 130 AND 133
 (AGRICULTURE)

TABLE II

RADAR SYSTEMS

POLYPANCHROMATIC DEVELOPMENT

4-8GHz TESTS

ULTRASONIC SIMULATION

THEORY OF IMPROVEMENT BY AVERAGING

SPACECRAFT IMAGING RADAR STUDY

DIGITAL SYNTHETIC APERTURE PROCESSOR

OPTIMUM DEPRESSION ANGLES SPECIFIED

SYSTEM FOR 1975 FLIGHT-SPECIFICATIONS

AIRCRAFT IMAGING RADAR

SUPPORT FOR REAL-APERTURE MOD. TO DPD-2

POLYPANCHROMATIC RADAR SPECIFICATIONS

COMPARISON OF AVERAGING IN REAL AND SYNTHETIC-APERTURE RADARS

SCATTEROMETER SYSTEMS

13. 3GHz SCATTEROMETER SYSTEM ERROR ANALYSIS

SCATTEROMETER DATA PROCESSING REQUIREMENTS

IMPROVED SCATTEROMETER CALIBRATION TECHNIQUES

TABLE III

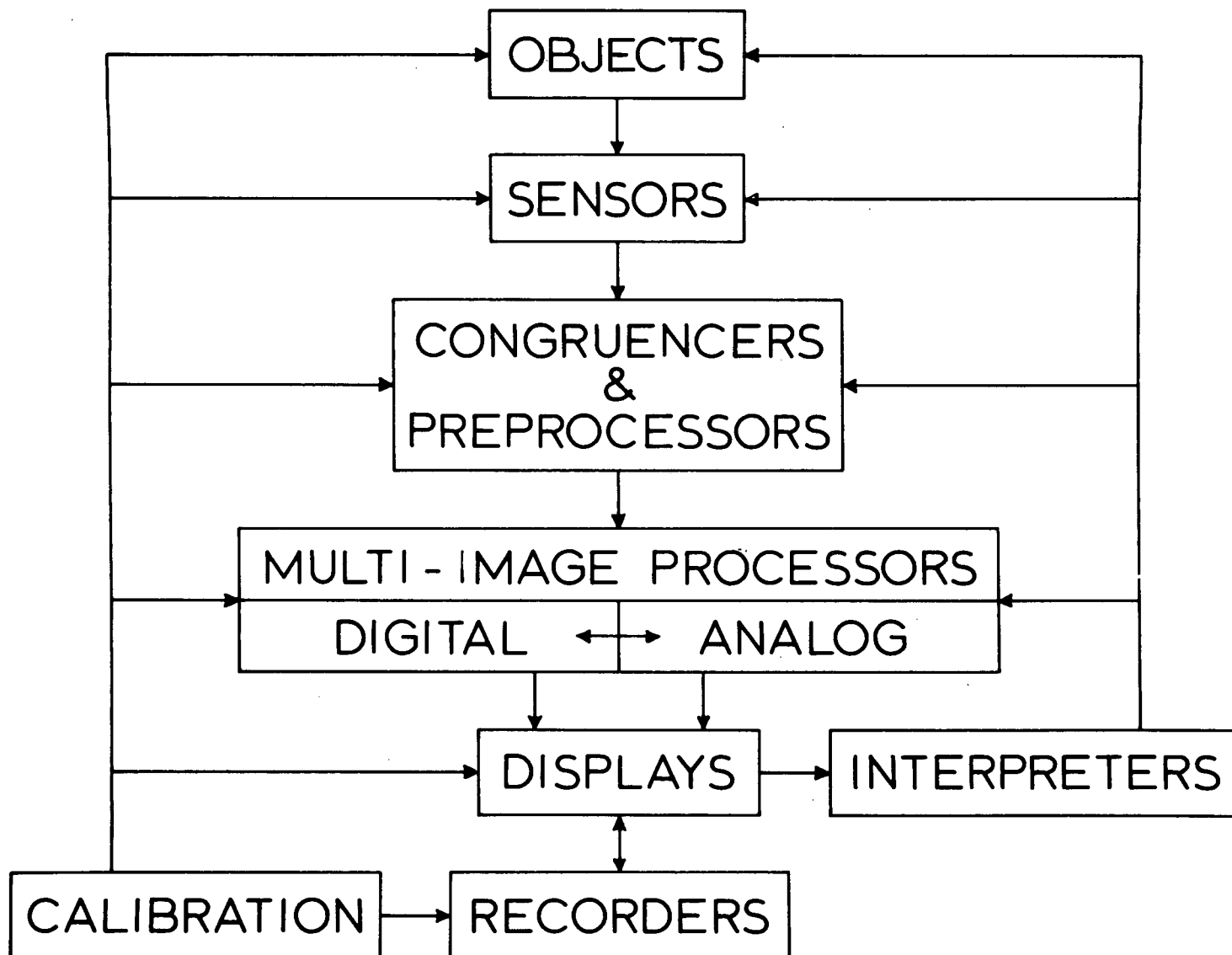
PROJECTED 1975 SYNTHETIC APERTURE
SPACE RADAR WITH DIGITAL PROCESSING

- RADAR PARAMETERS -

SWATH	40km	ANTENNA LENGTH	4m
ALTITUDE	1080km	FREQUENCY	10 GHz
INCIDENT ANGLE	30°	RESOLUTION	30m
σ° RANGE	-20 TO +20 dB	AV. TRANS. POWER	60w

- PROCESSOR -

SUBAPERTURES	10	TOTAL POWER	200w
TOTAL STORAGE	4.8 MBITS	VOLUME	0.15m ³
POWER TO STORAGE	48w	WEIGHT	30kg
(10μW/ BIT)			



THE REMOTE SENSING SYSTEM

Figure 1

SPECTRAL RESPONSES OF OBJECTS OVER OCTAVE BANDWIDTHS

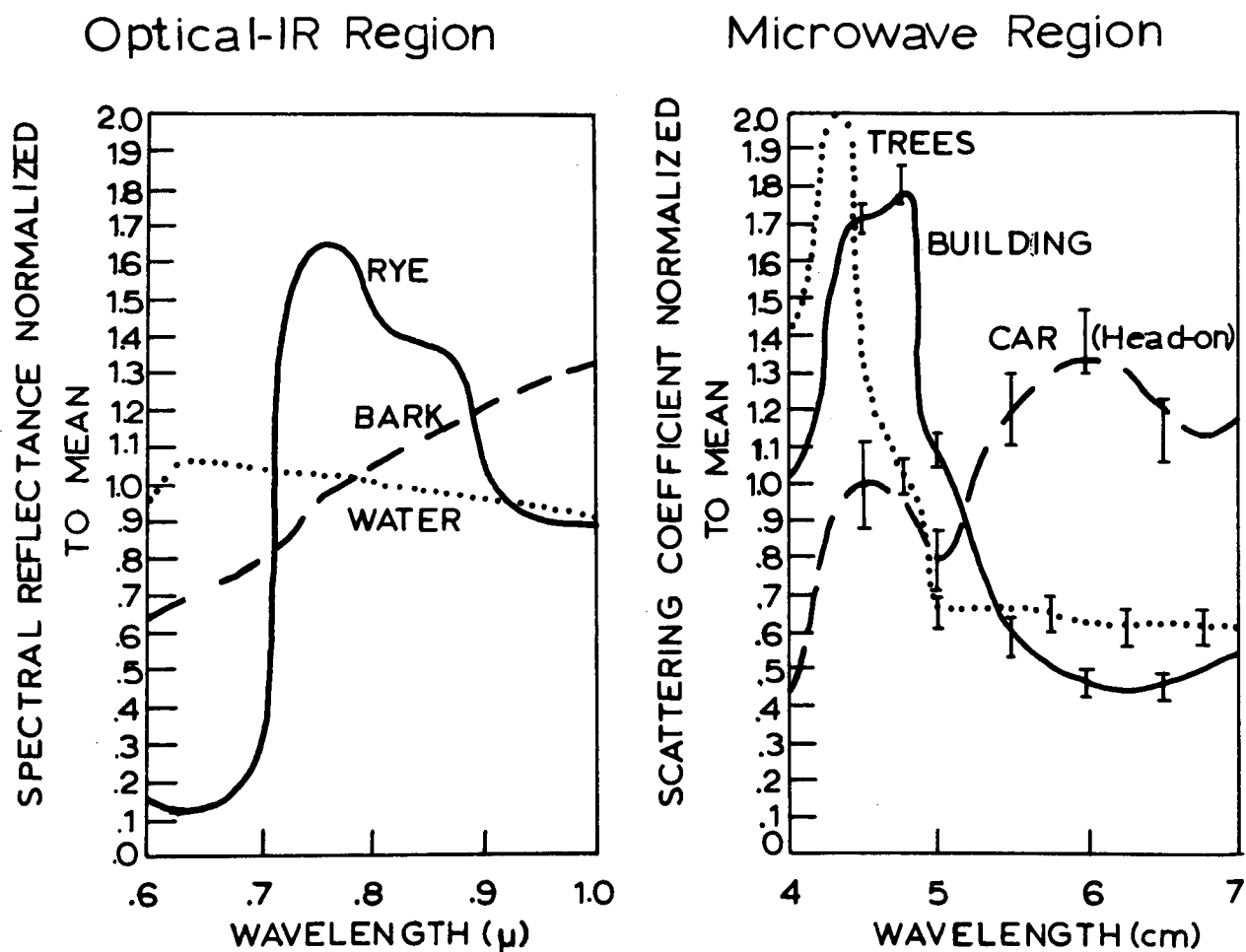
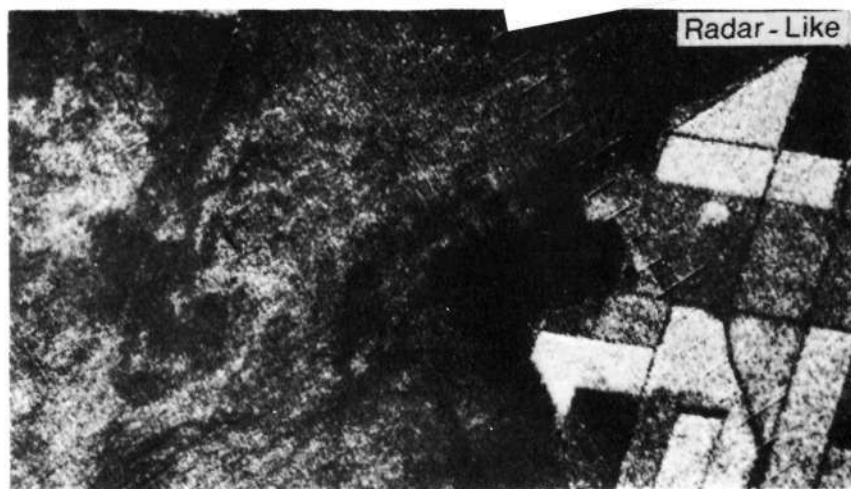


Figure 2

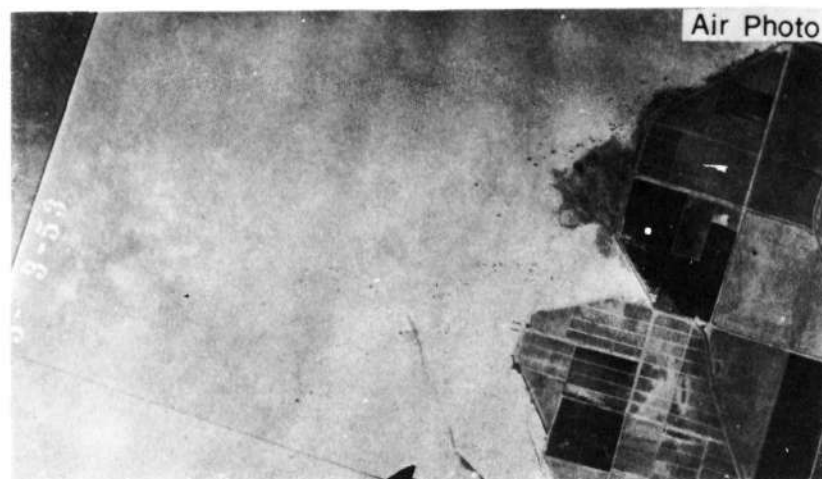


MONOCHROMATIC

NOT REPRODUCIBLE



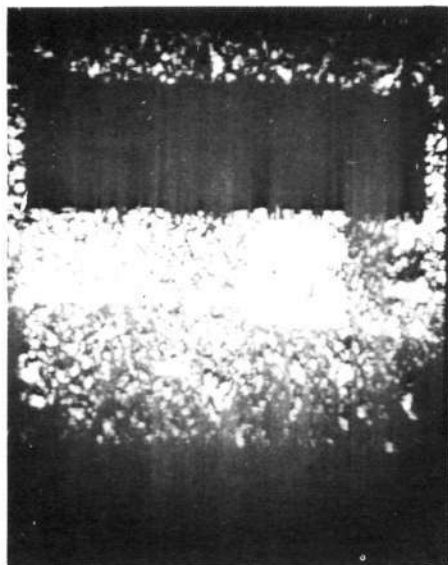
MONOCHROMATIC



PANCHROMATIC

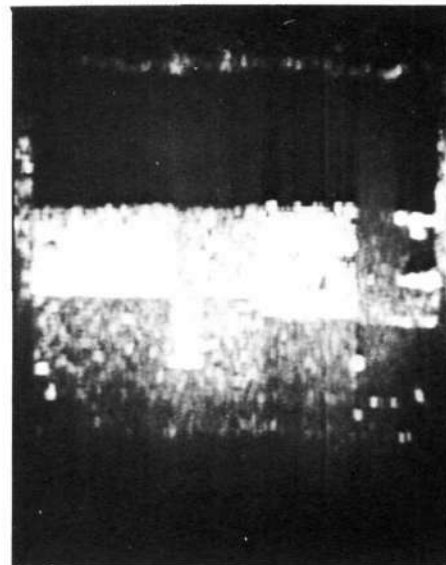
Figure 3

COMPARISON OF MONOCHROMATIC AND
PANCHROMATIC AIR PHOTOS WITH
MONOCHROMATIC RADAR IMAGE.



MONOCHROMATIC IMAGE

$F = 1700 \text{ kHz}$



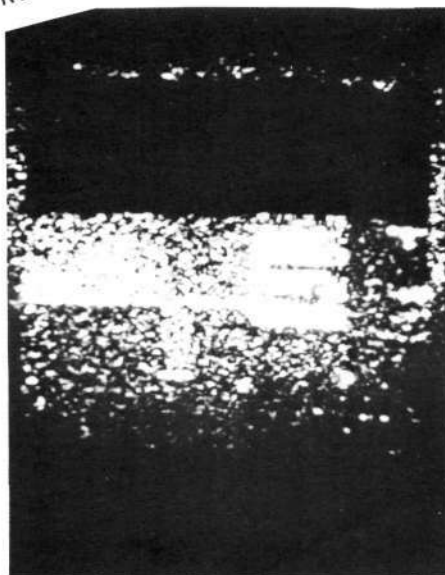
PANCHROMATIC IMAGE

$F = 1200 - 2000 \text{ kHz}$

NOT REPRODUCIBLE

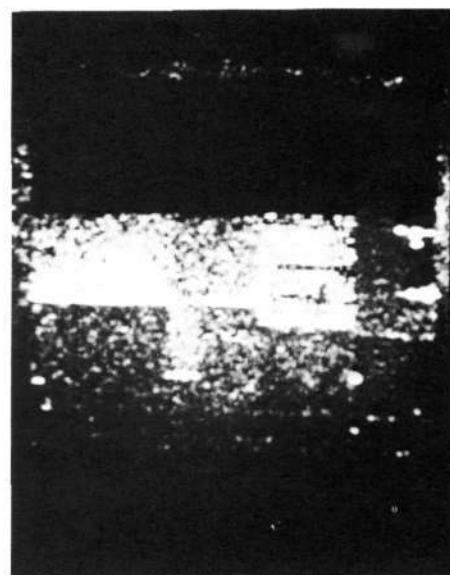
$\tau = 20 \text{ } \mu\text{SEC.}$

$\theta \approx 30^\circ$



MONOCHROMATIC IMAGE

$F = 1600 \text{ kHz}$



PANCHROMATIC IMAGE

$F = 1200 - 2000 \text{ kHz}$

$\tau = 9 \text{ } \mu\text{SEC.}$

$\theta \approx 31^\circ$

Figure 4

ACOUSTIC SIDE-LOOKING RADAR IMAGES OF AGRICULTURAL MODEL DEMONSTRATING
IMPROVEMENT OF SENSING WITH PANCHROMATIC ILLUMINATION.

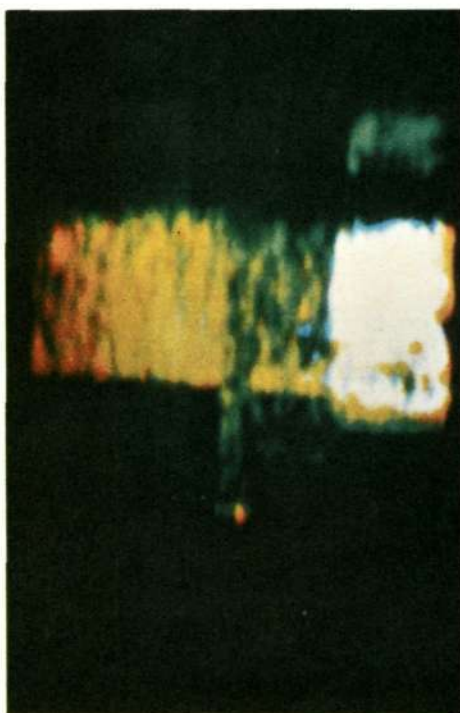
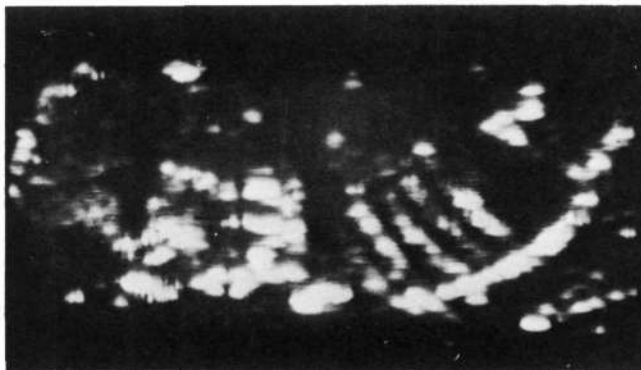
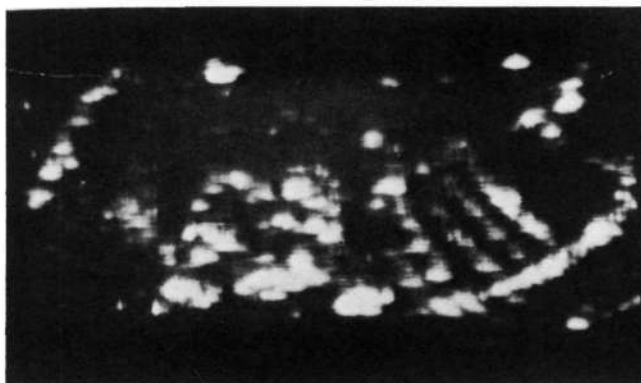


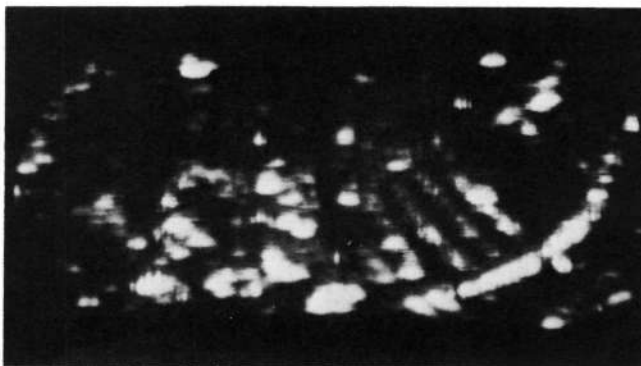
Figure 5. Ultrasonically simulated polypanchromatic radar image. Different colors indicate different materials distinguished by their spectral response.



(a) $f = 6.00$ GHz

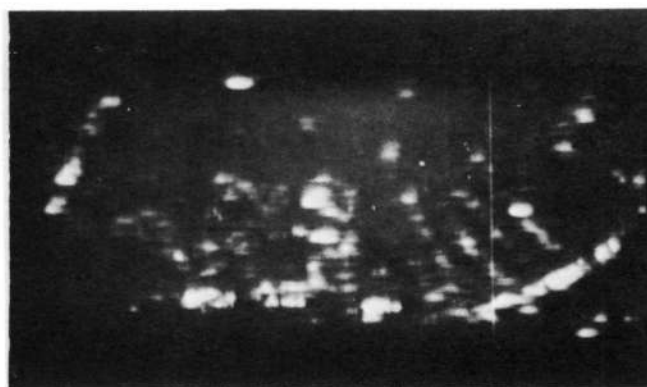


(b) $f = 5.95$ GHz

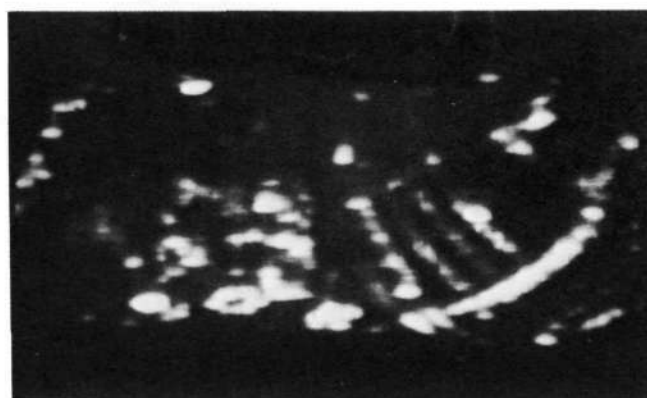


(c) $f = 6.05$ GHz

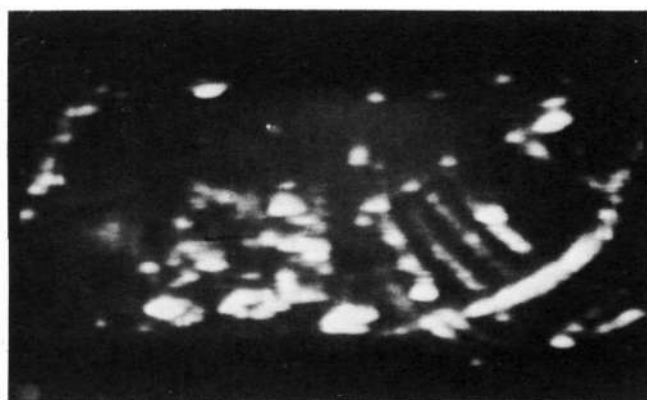
Figure 6. Monochromatic images taken at slightly different frequencies



(a) Monochromatic $f = 6.00$ GHz

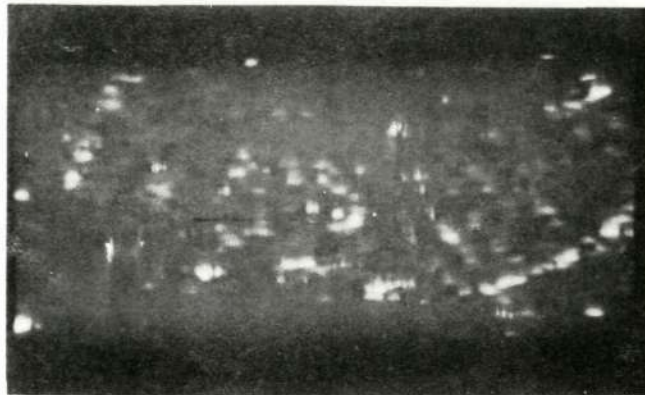


(b) Panchromatic $f = 6.00 \pm 0.25$ GHz



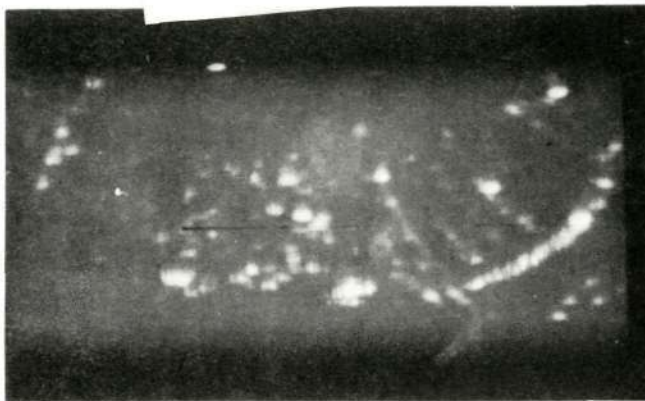
(c) Panchromatic $f = 6.00 \pm 0.50$ GHz

Figure 7. Comparison of monochromatic and panchromatic images

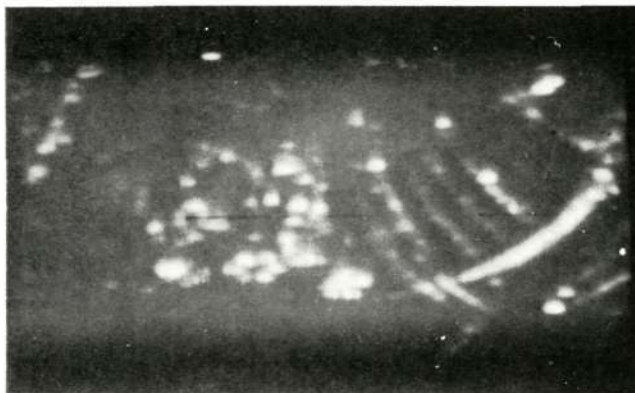


(a) Monochromatic $f = 7.50$ GHz

NOT REPRODUCIBLE



(b) Panchromatic $f = 7.50 \pm 0.25$ GHz



(c) Panchromatic $f = 7.50 \pm 0.50$ GHz

Figure 8. Comparison of monochromatic and panchromatic images

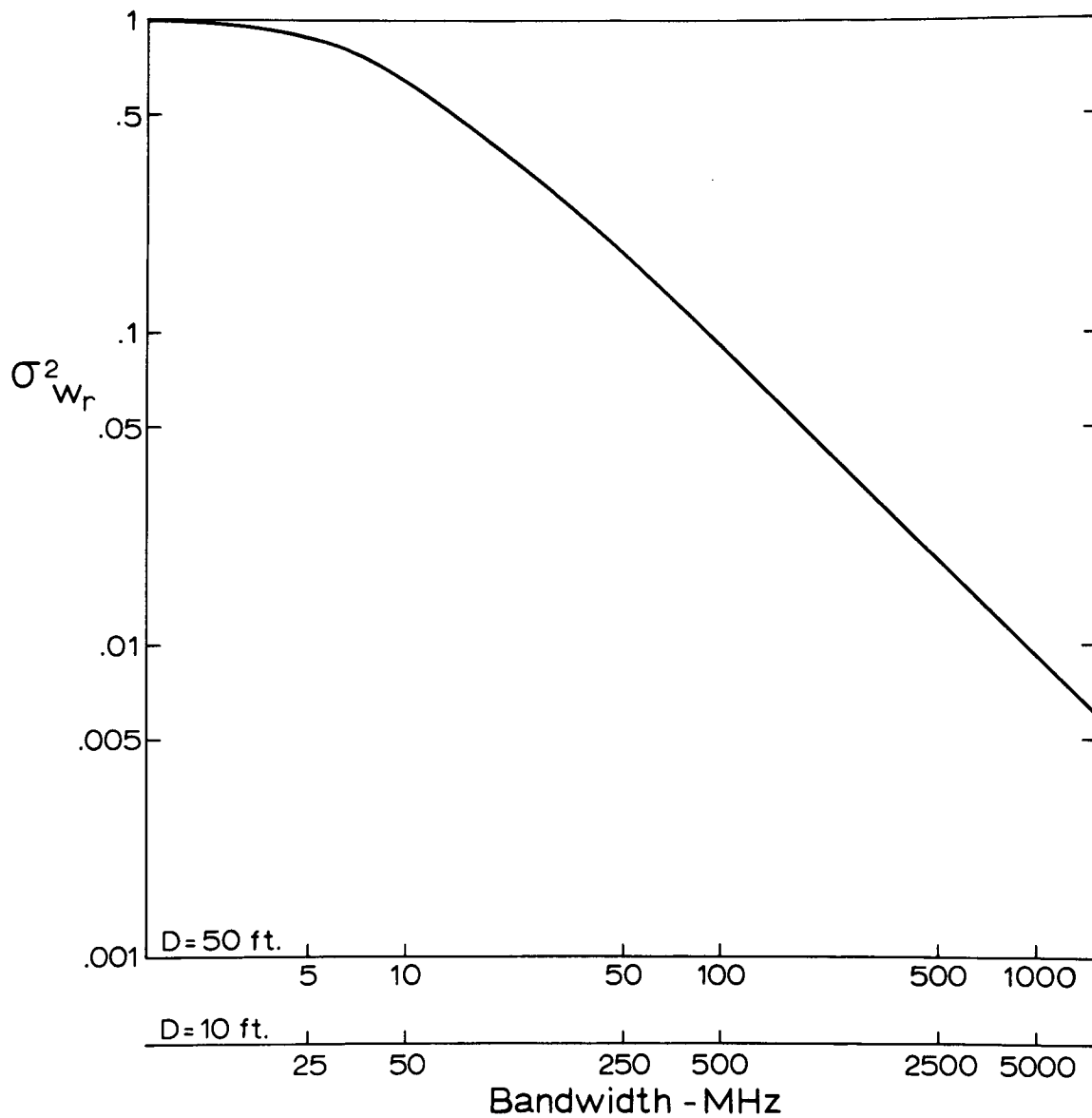


Figure 9. Variance of received power vs averaging bandwidth

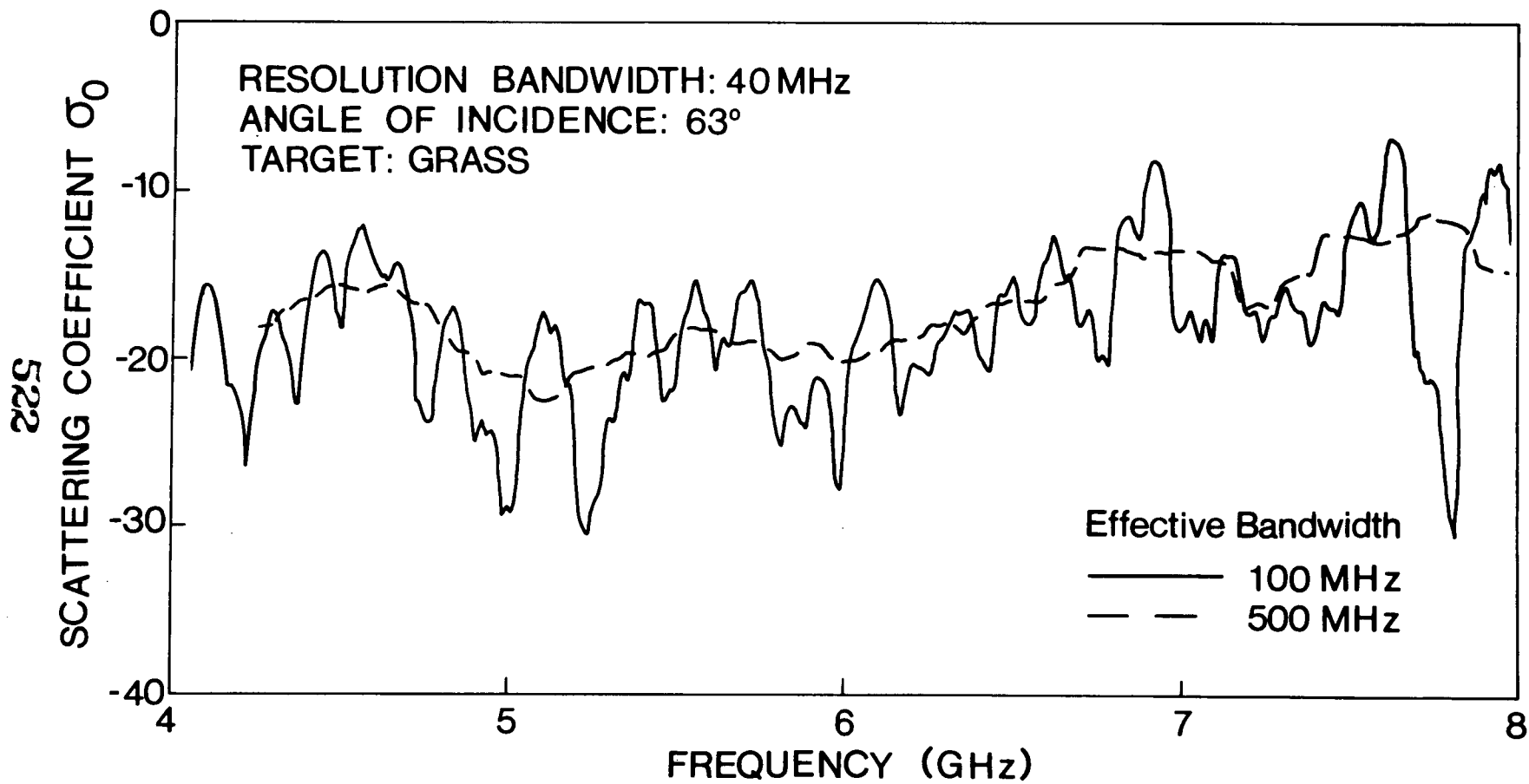
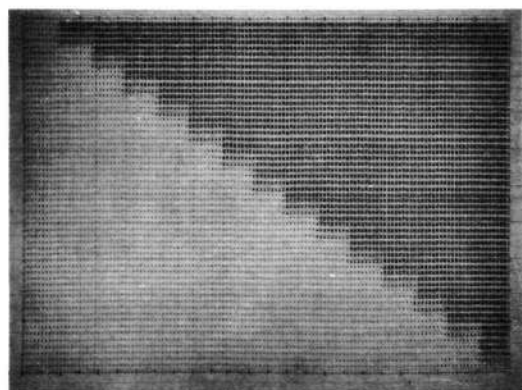
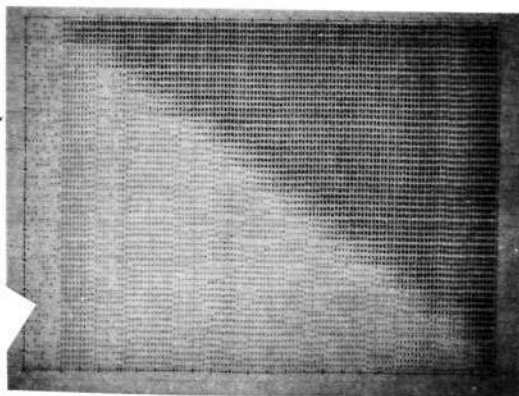


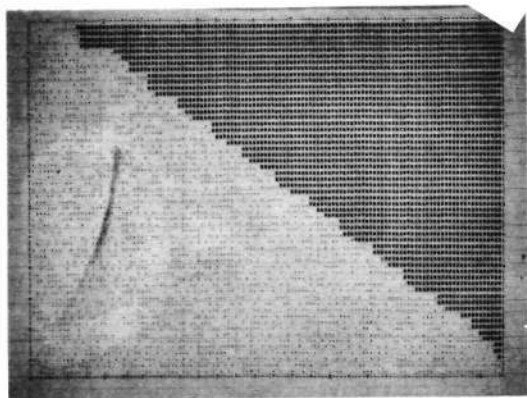
Figure 10. Example of fading that causes speckle in radar images



(1)



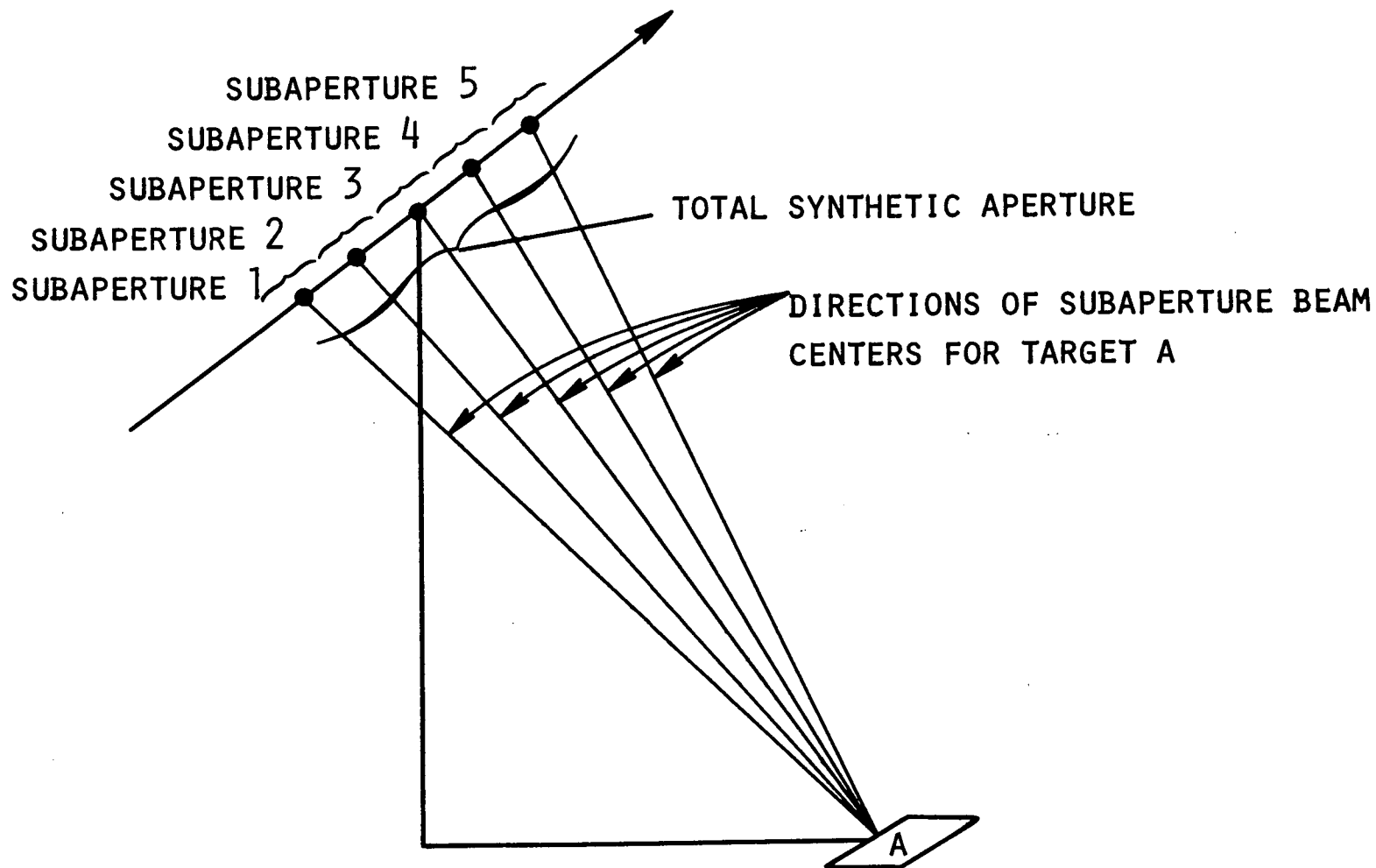
(2)



(3)

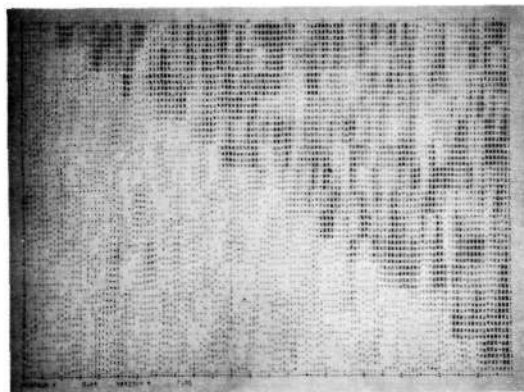
→
Flight direction

Figure 11. Fully Focused synthetic aperture imaging over a boundary separating two fields whose non-statistically distributed scattering cross section differ by 9.54 db. (1) "True" map of fields, (2) SAR image with dynamic range of display matched to image dynamic range, (3) SAR image with picture dynamic range much smaller than image range.

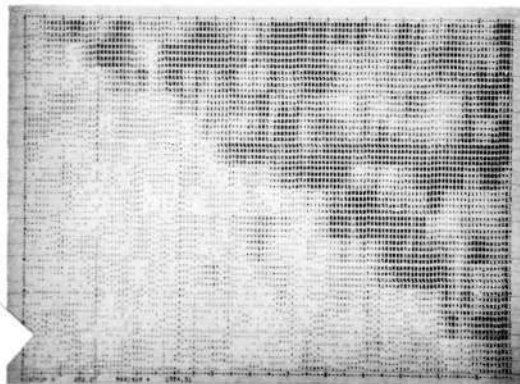


SYNTHETIC APERTURE DIVIDED INTO 5 SUBAPERTURES
 THEORETICAL RESOLUTION 2.5X (REAL APERTURE)
 IMAGE (MEAN/STD.DEV.) IMPROVED BY $\sqrt{5}$

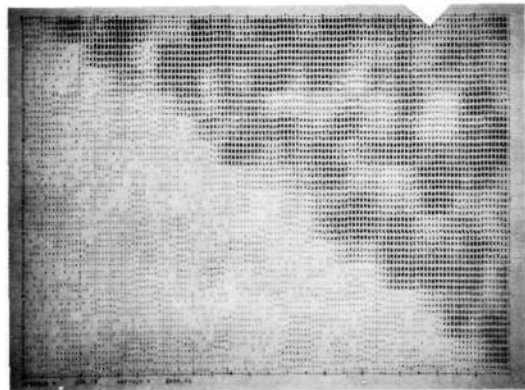
Figure 12. Use of multiple subapertures to improve grey scale



(1)



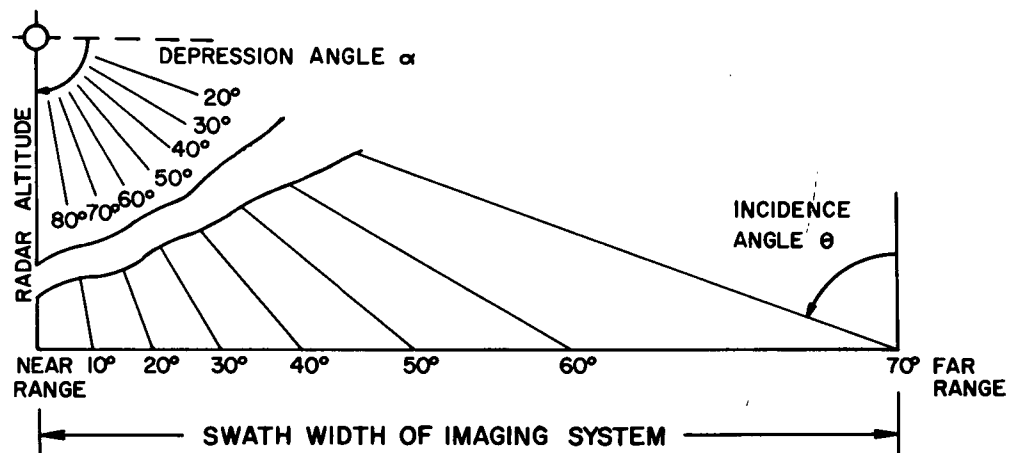
(2)



(3)

→
Flight direction

Figure 13. (1) "True" map of Rayleigh distributed scattering cross sections for 2 fields whose differential scattering cross sections differ by 9.54 db — $M/STD \approx \sqrt{3.6}$; (2) non-quadrature subaperture processing — 5 subapertures — $M/STD \approx \sqrt{9.0}$; (3) quadrature subaperture processing — 5 subapertures — $M/STD \approx \sqrt{18.0}$.



526

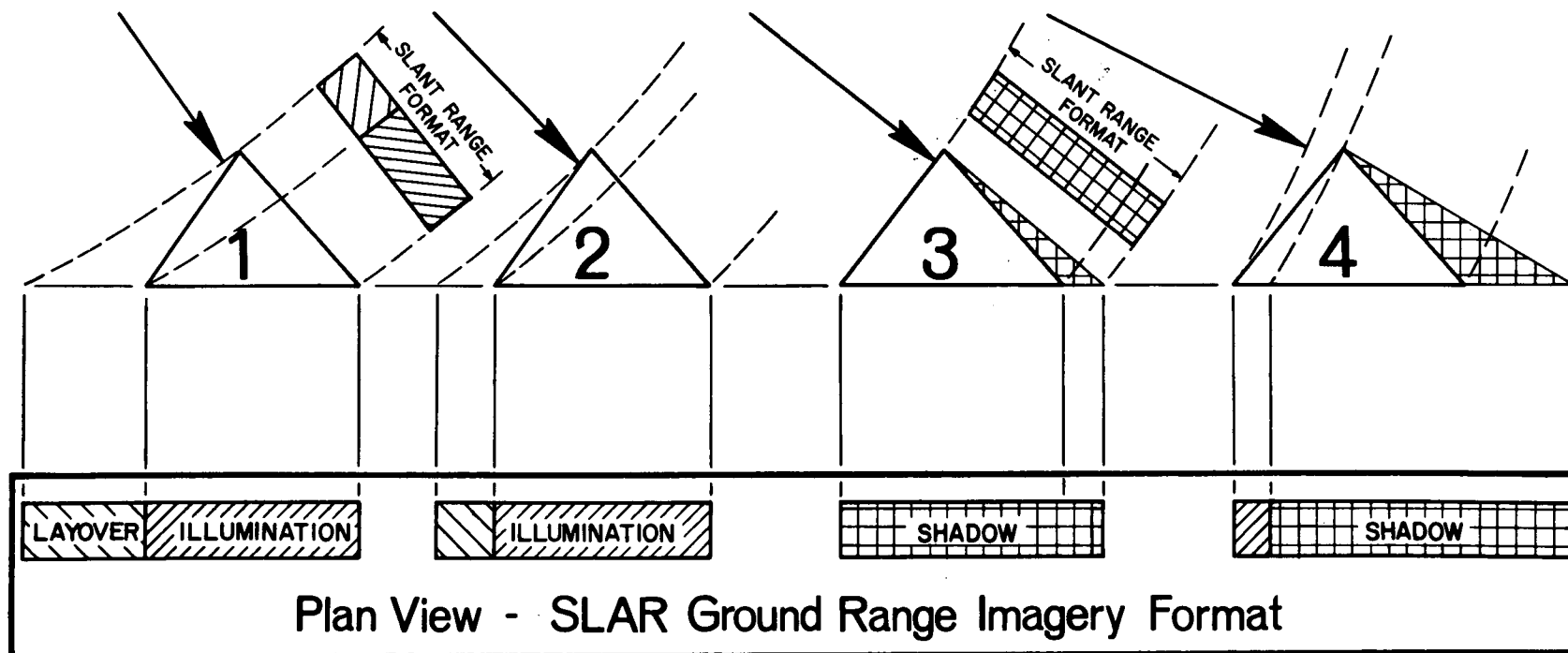
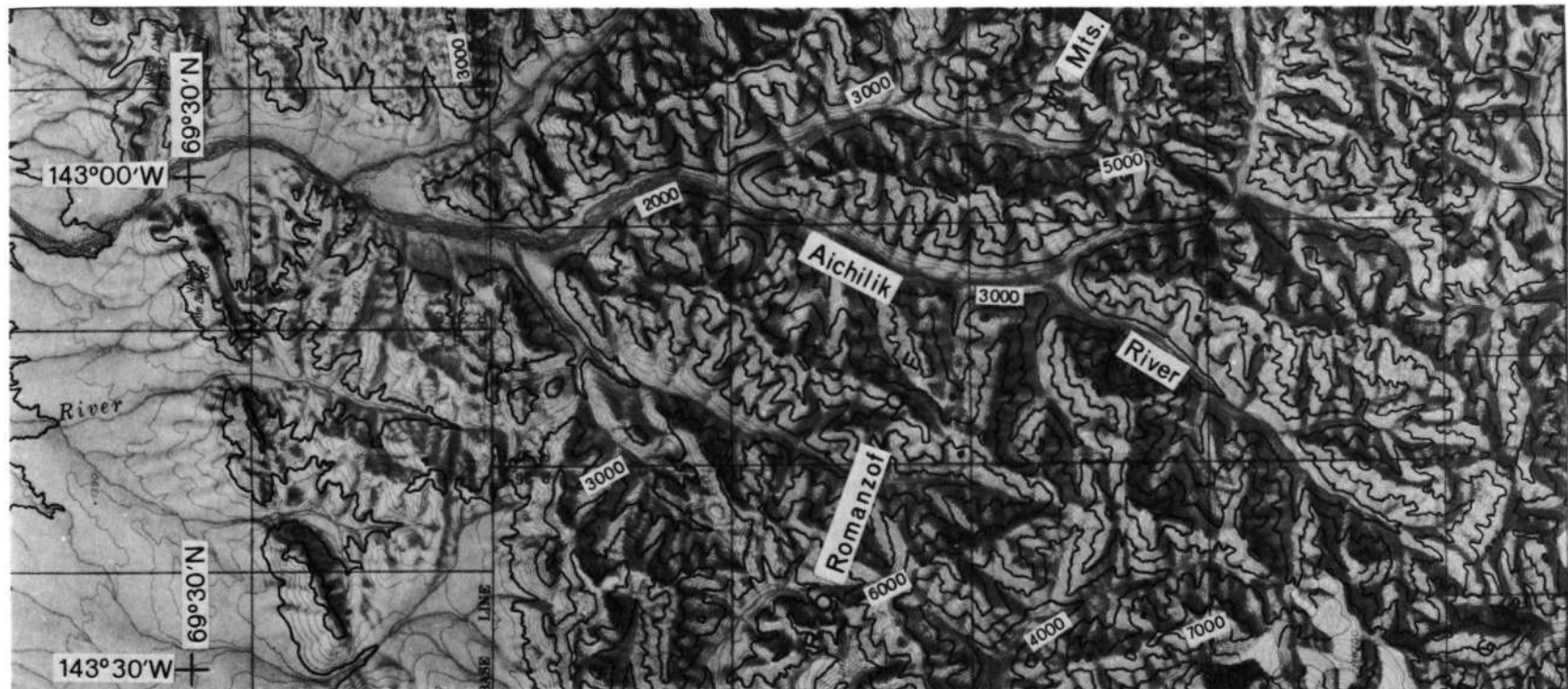


Figure 14. Radar shadow and layover vs angle

AICHILIK RIVER AREA, ALASKA



Contour Interval 200 ft.
Heavy Contour Interval 1000 ft.

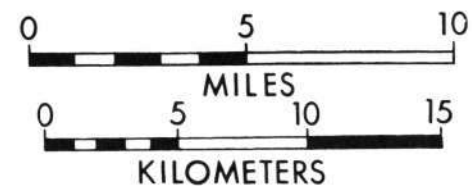
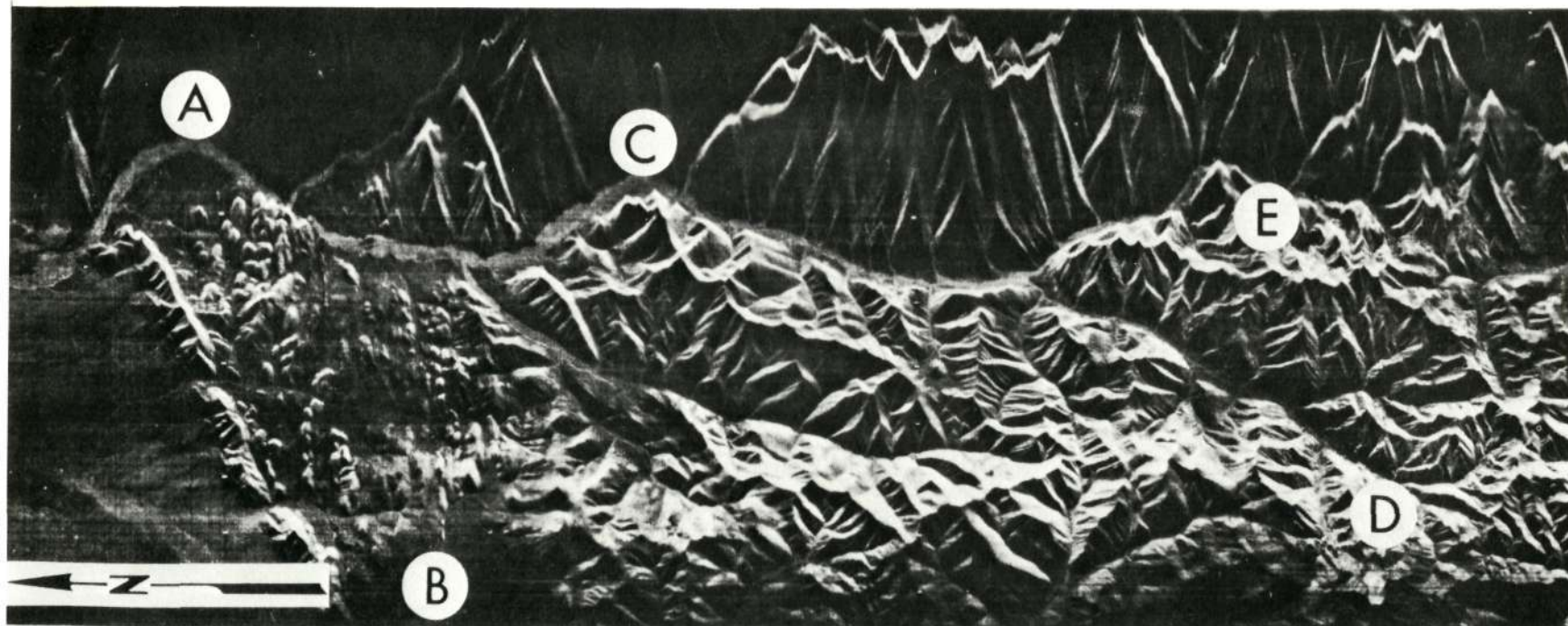


Figure 15. Contour map to go with figure 16

NOT REPRODUCIBLE



GROUND RANGE RADAR



AICHILIK RIVER AREA, ALASKA

Figure 16. Example of "true ground range" presentation in mountainous terrain

CASCADE GLACIER AREA, WASHINGTON

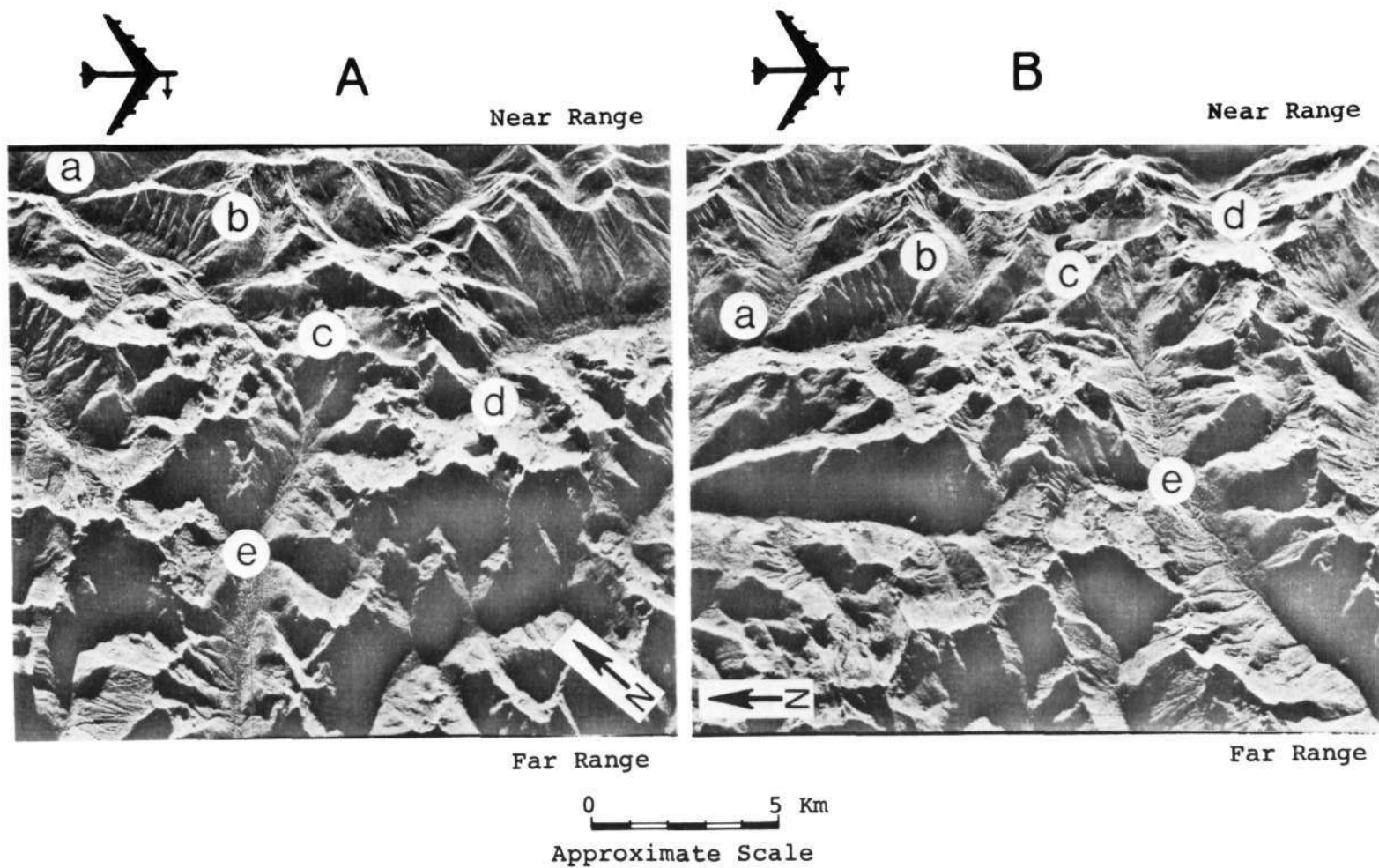


Figure 17. Illustration of radar layover and shadow using different look-angles for the same terrain and slant range presentation

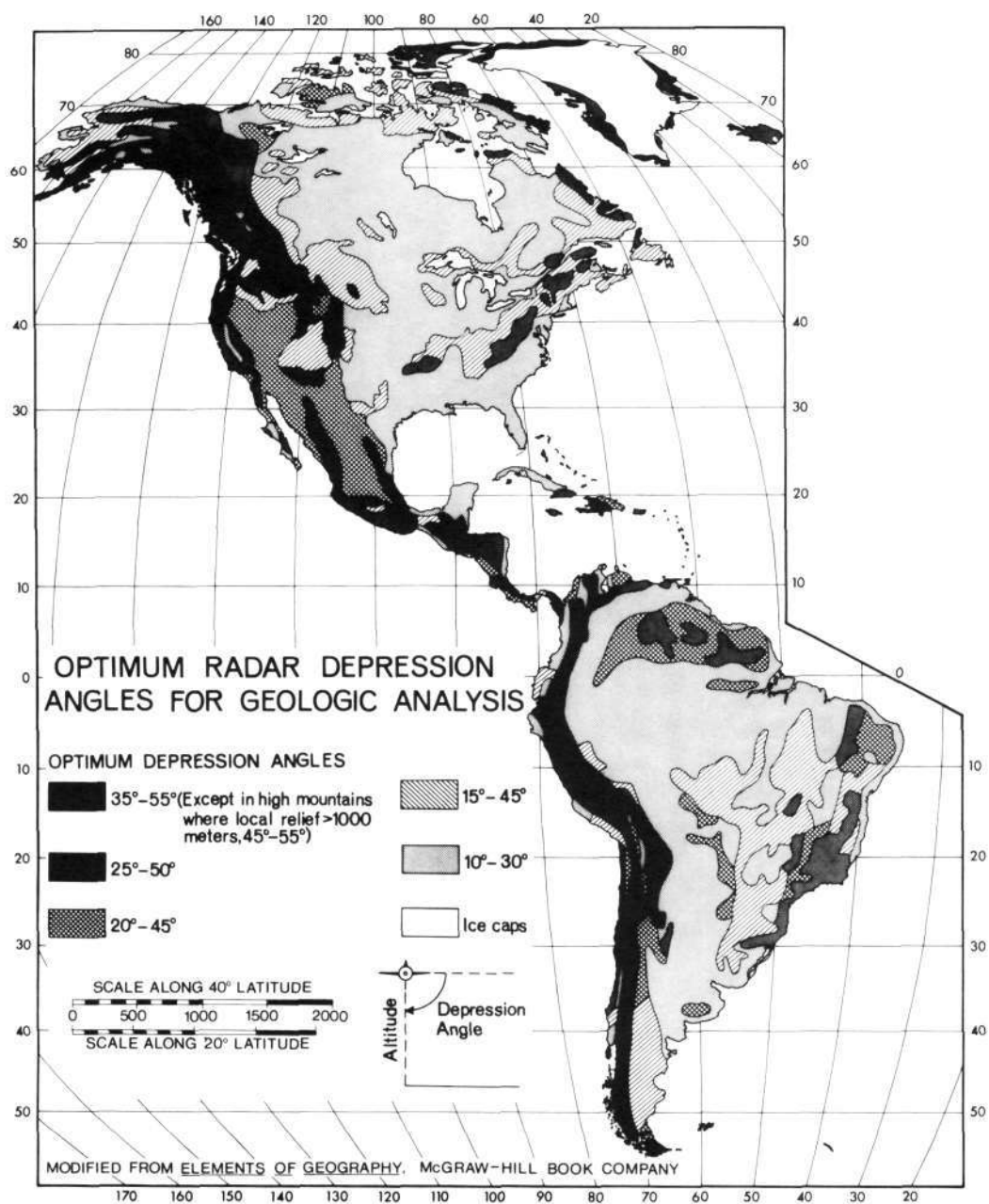


Figure 18

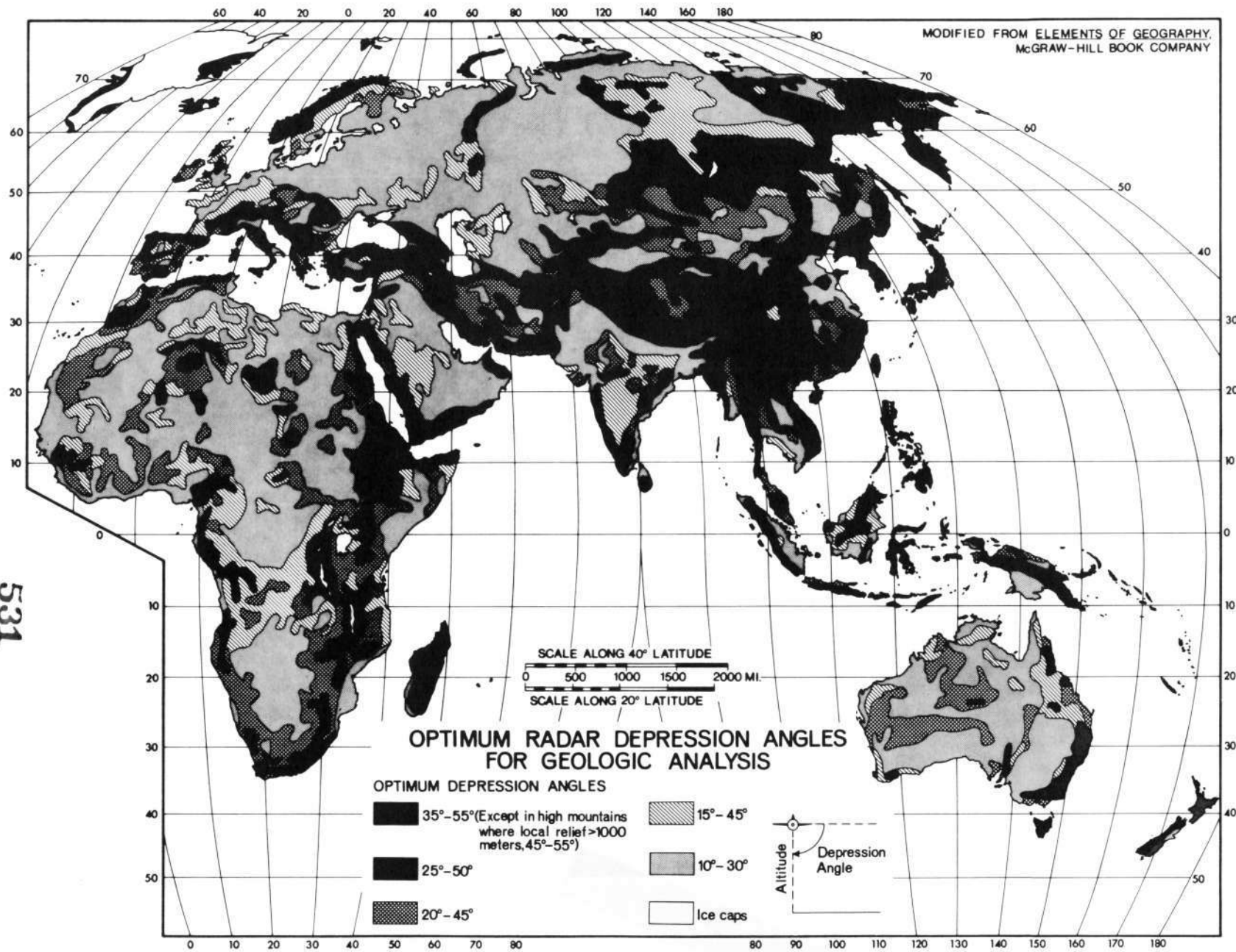
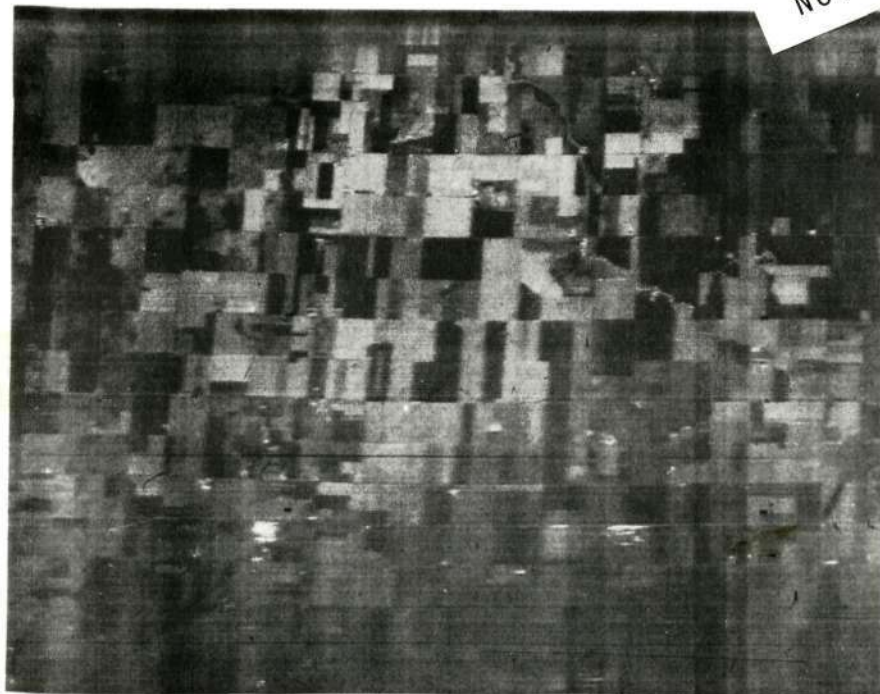
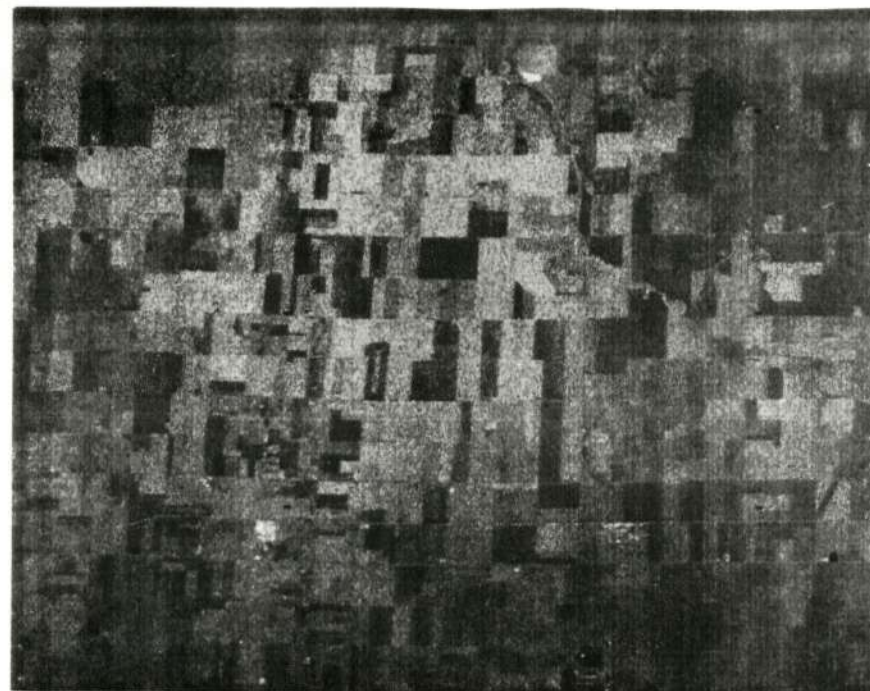


Figure 19

NOT REPRODUCIBLE



REAL



SYNTHETIC

COMPARISON OF REAL AND SYNTHETIC APERTURE DPD-2 IMAGES

GARDEN CITY, KANSAS 1970

Figure 20

532

41-36

ADDENDUM

RESEARCH SUPPORTED BY NASA/MSC CONTRACT NAS 9-10261

Center for Research, Inc., University of Kansas

- *"Multi-Image Pattern Recognition Ideas and Results," R. M. Haralick,
Ph. D. Dissertation, CRES Technical Report 133-11, September,
1969.
- *"A Novel Interface for a Man-Machine Display System," G. L. Kelly
and J. A. Lucas, International Symposium on Man-Machine
Systems, 8-12 September 1969, IEEE Conference Record No.
69C58-MMS.
- "Radar Sensing in Agriculture, A Socio-Economic Viewpoint," S. A.
Morain, J. Holtzman, and F. Henderson, Presented at EASCON
1970. Also CRES Technical Report 177-14.
- "Cholame Area - San Andreas Fault Zone, California - A Study in SLAR,"
R. S. Wing, Modern Geology, vol. 1, 1970, pp. 173-186. Also
CRES Technical Report 118-10.
- *"Snowfield Mapping with K-Band Radar," W. P. Waite and H. C. MacDonald
Remote Sensing of Environment, vol. 1, no. 2, 1970.
- *"Effects of Roughness on Emissivity of Natural Surfaces in the Microwave
Region," F. T. Ulaby and A. K. Fung, 1970 Southwest IEEE
Conference.
- *"Using Radar Imagery for Crop Discrimination: A Statistical and Conditional
Probability Study," R. M. Haralick, F. Caspall, and D. S.
Simonett, Remote Sensing of Environment, vol. 1, no. 2, 1970.
- *"Interpretive and Mosaicking Problems of SLAR Imagery," A. J. Lewis
and H. C. MacDonald, Remote Sensing of Environment, vol. 2.
- *"The Apparent Temperature with Emissivity of Natural Surfaces at Micro-
wave Frequencies," F. T. Ulaby, A. K. Fung, and S. Wu,
March, 1970, CRES Technical Report 133-12.
- *"Broad Spectrum Electromagnetic Backscatter," W. P. Waite, Ph. D.
Dissertation, CRES Technical Report 133-17, 1970.
- *"Worldwide Oceanic Wind and Wave Predictions Using a Satellite Radar
Radiometer," R. K. Moore and W. J. Pierson, AIAA Technical
Paper No. 70-310. Presented at AIAA Earth Resources Observations
and Information Systems Meeting, March 2-4, 1970, Anapolis,
Maryland.

"Ground Return," Chapter 25 in: Radar Handbook, M. I. Skolnik, ed., R. K. Moore contributor, McGraw-Hill Book Co., New York, May, 1970.

*"Remote Sensing with Imaging Radar: A Review," D. S. Simonett, 1970, Commission VI- International Society of Photogrammetry Meeting, Dresden, Germany, Summer, 1970.

*"A High Speed Disc Memory and a Color Image Display for a Small Computer," J. Lucas, Ph. D. Dissertation, CRES Technical Report 133-20, August, 1970.

*"Spectral Reflectivity Data: A Practical Acquisition Procedure," D. D. Egbert, Master's Thesis, CRES Technical Report 133-21, November, 1970.

"Technique for Producing a Pseudo-Three-Dimensional Effect with Monoscopic Radar Imagery," L. F. Dellwig, H. C. MacDonald, and J. N. Kirk, Photogrammetric Engineering, September, 1970.

"Soil Moisture Detection with Imaging Radars" H. C. MacDonald and W. P. Waite, CRES Reprint 177-1, 1970.

"Interface of PDP-15/20 and 201A1 Data Set," Parveen K. Gupta, Master's Thesis, September, 1970, University of Kansas, Electrical Engineering Department.

"Radar Uses for Natural Resources Inventories in Arid Zones," S. A. Morain, Symposium in Mexico, November, 1970. In press — McGraw-Hill of Mexico.

"An Analysis of RF Phase Error in the 13.3 GHz Scatterometer," G. A. Bradley, November, 1969, Technical Memorandum 177-1.

"Mathematical Theory of Filtering Program," R. M. Haralick, December, 1969, Technical Memorandum 177-2.

"Informal Log, 13.3 GHz Single-Polarized Scatterometer, 400 MHz Dual-Polarized Scatterometer, Mission 119, Argus Island, Bermuda, 19 January 1970 - 27 January 1970," G. A. Bradley, February, 1970, Technical Memorandum 177-4.

"Principal Component Analysis," R. M. Haralick, April, 1970, Technical Memorandum 177-5.

"Informal Log, Mission 126, Pt. Barrow, Alaska," G.A. Bradley, June, 1970, Technical Memorandum 177-6.

"Frequency Averaging for Imaging Radars," G. C. Thomann, June, 1970, Technical Memorandum 177-7.

- "Informal Log, Mission 130, Garden City, Kansas," J. D. Young, May, 1970, Technical Memorandum 177-9.
- "Ninety-Day Mission Analysis Report, Mx 108, DPD-2, Side-Look Radar, Pisgah Crater, California," L. F. Dellwig, July, 1970, Technical Memorandum 177-10.
- "Correlated Averaging to Enhance Radar Imagery," Ralph W. Gerchberg, September, 1970, Technical Memorandum 177-11.
- "Analysis of Sea State Missions 20-60," J. Young, September, 1970, Technical Memorandum 177-12.
- "A Note on the Antenna Beamwidth Term Used in the Scatterometer Data Reduction Program," J. D. Young and G. A. Bradley, October, 1970, Technical Memorandum 177-13.
- "An Analysis of Methods for Calibrating the 13.3 GHz Scatterometer," G. A. Bradley, Technical Report 177-1.
- "Signal Analysis of the Single-Polarized 13.3 GHz Scatterometer," G. A. Bradley, May, 1970, Technical Report 177-2.
- "Image Textural Analysis by a Circular Scanning Technique," G. O. Nossaman, M. S. Thesis, June, 1970, Technical Report 177-3.
- "A Regional Study of Radar Lineaments Patterns in the Ouachita Mountains, McAlester Basin — Arkansas Valley, and Ozark Regions of Oklahoma and Arkansas," J. N. Kirk, June, 1970, Technical Report 177-4.
- "An Analysis of the Effects of Aircraft Drift Angle on Remote Radar Sensors," G. A. Bradley and J. D. Young, August, 1970, Technical Report 177-5.
- "Radar Lineament Analysis, Burning Springs Area, West Virginia — An Aid in the Definition of Appalachian Plateau Thrusts," R. S. Wing, W. K. Overbey, Jr., and L. F. Dellwig, July, 1970, Technical Report 177-6.
- "An Evaluation of Fine Resolution Radar Imagery to Making Agricultural Determinations," S. A. Morain, J. Coiner, August, 1970, Technical Report 177-7.
- "Optimum Radar Depression Angles for Geological Analysis," H. C. MacDonald and W. P. Waite, August, 1970, Technical Report 177-9.

*Supported partially by NASA Contract NAS 9-10261, U. S. Army THEMIS Contract DAAK02-68-C-0089, or NOO Contract N60921-C-0221.